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The discovery of rapid oscillations in the magnetic Ap stars HD 69013 and HD 96237*

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ABSTRACT

We report the detection of short-period variations in the stars HD 69013 and HD 96237. These stars possess large overabundances of rare earth elements and global magnetic fields, thus belong to the class of chemically peculiar Ap stars of the main sequence. Pulsations were found from analysis of high time resolution spectra obtained with the European Southern Observatory (ESO) Very Large Telescope using a cross-correlation method for wide spectral bands, from lines belonging to rare earth elements and from the Hα core. Pulsation amplitudes reach more than 200 m s^{-1} for some lines in HD 69013 with a period of 11.4 min and about 100 m s^{-1} in HD 96237 with periods near 13.6 min. The pulsations have also been detected in photometric observations obtained at the South African Astronomical Observatory.

Key words: stars: chemically peculiar – stars: magnetic field – stars: oscillations.

1 INTRODUCTION

The rapidly oscillating Ap (roAp) stars are magnetic main-sequence stars that pulsate in high radial overtone p modes with periods in the range of 5.7–21 min. They show broad-band photometric amplitudes less than 0.01 mag, whereas rapid radial velocity variations in rare earth element lines can reach several km s^{-1} (e.g. Kurtz 1990; Freyhammer et al. 2009). The roAp stars are important targets for the study of the interactions among chemical anomalies, magnetic field and pulsations. These stars show abnormal atmospheric structure with chemical stratification (Cowley et al. 2001; Ryabchikova et al. 2002). The pulsations of these stars also make them promising objects for interior model testing using asteroseismology (Aerts, Christensen-Dalsgaard & Kurtz 2010). The roAp stars were discovered by Kurtz (1982); at present more than 40 such stars are known.

Interesting and surprising discoveries have been made in recent years, which give new insight in the study of pulsating Ap stars. New ground is being broken with µmag precision photometric data from the *Kepler* Mission. Balona et al. (2010) discovered an roAp star that pulsates in both high overtone p modes and a low-frequency g mode, opening up the possibility of better modelling of the interiors of these most peculiar stars.

In 2007, we started a high-resolution survey of cool chemically peculiar stars based mostly on the photometric catalogue of Martinez (1993). One of the goals of the survey is to select stars with high peculiarity and strong magnetic field and to determine their fundamental parameters to select the most promising candidates to be roAp stars. Nearly 400 stars have been observed and many of them are good roAp candidates for further high time resolution spectroscopic and photometric observations. For several of these stars we have obtained such observations and here we present the discovery of pulsations for two objects, HD 69013 and HD 96237.

Both stars were in the list of stars with magnetically split spectral lines found by Freyhammer et al. (2008). HD 69013 is a typical cool Ap star; HD 96237 is more impressive with significant spectral variability. The physical parameters $T_{\rm eff}$ and $\log g$ indicate that HD 69013 and HD 96237 are both main-sequence stars, situated in the Hertzsprung–Russell (HR) diagram where the instability strip crosses the main sequence. For many Ap stars in this region of main sequence rapid oscillations have been detected, therefore both stars were promising objects for pulsation testing.

2 OBSERVATIONS AND DATA REDUCTION

High time resolution spectroscopic observations were carried out at the European Southern Observatory (ESO) using the Ultraviolet and Visual Echelle Spectrograph (UVES) installed at Unit Telescope 2 (UT2) of the Very Large Telescope (VLT). For HD 69013, data were obtained during two high time resolution observing runs on 2008

*Based on observations collected at the ESO, Chile, as part of programmes 080.D-0191(A), 078.D-0192(A) and 078.D-0080(A).
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Table 1. A journal of observations of HD 69013. The columns give the Julian Date (JD) of the start of exposure, the observation time and the number of spectra or photometric measurements.

JD	Observation time (min)	Exposures number	Telescope
245 4482.546	57	34	ESO UT2 VLT
245 4502.549	57	34	ESO UT2 VLT
245 5226.448	121	362	SAAO 1-m
245 5229.377	84	252	SAAO 1-m

Table 2. A journal of observations of HD 96237. The columns are the same as for Table 1.

JD	Observation time (min)	Exposures number	Telescope
245 4540.515	57	34	ESO UT2 VLT
245 5225.501	118	354	SAAO 1-m
2455228.438	100	301	SAAO 1-m
245 5229.486	90	541	SAAO 1-m
245 5235.483	58	184	SAAO 1-m
245 5329.226	224	1256	SAAO 0.5-m

January 17 and February 6. For each run 34 spectra were obtained with exposure times of 80 s and readout and overhead times of ∼21 s, corresponding to a time resolution of ∼101 s. For HD 96237 we obtained 34 spectra on 2008 March 15 with the same exposure and readout times. The wavelength region observed is λλ4970–7010 Å, with a small gap in the region around 6000 Å caused by the space between the two CCDs. The average spectral resolution is about $R = 10^5$. The CCD frames were processed using the UVES pipeline to extract and merge the echelle orders to 1D spectra that were normalized to the continuum.

We also obtained photometric observations of HD 69013 and HD 96237 in 2010 January, February and May. These observations were obtained at the South African Astronomical Observatory (SAAO) in Johnson *B* filter with the 1-m telescope and SAAO CCD and STE4 detector and with the modular photometer at the 0.5-m telescope. The reduction of photometric observations was done with ESO-MIDAS software and with software developed at SAAO. The lists of the observations are shown in Tables 1 and 2.

3 PULSATION SEARCH AND ANALYSIS

For roAp stars lines of rare earth elements show higher pulsation amplitudes, while the lines of other chemical species, including light elements and iron peak elements, show much smaller pulsation amplitude or show none at all (see, e.g. Malanushenko, Savanov & Ryabchikova 1998; Kurtz, Elkin & Mathys 2007). This strange behaviour is explained by stratification where rare earth elements concentrate in the upper layers of the stellar atmosphere where oscillation amplitudes reach a maximum, while most other chemical elements tend to concentrate in deeper layers where the pulsation amplitude is lower. Lines of iron peak elements in roAp stars show very low pulsation amplitude or none at all (Kochukhov & Ryabchikova 2001; Elkin, Kurtz & Mathys 2008).

To search for rapid radial velocity variability we performed cross-correlation of sections of the spectrum using ESO-MIDAS software. We also measured the central positions for profiles of individual spectral lines by the centre of gravity method. Frequency analyses of radial velocity and photometric time series were performed using ESO-MIDAS's time series analysis and a discrete Fourier transform programme by Kurtz (1985).

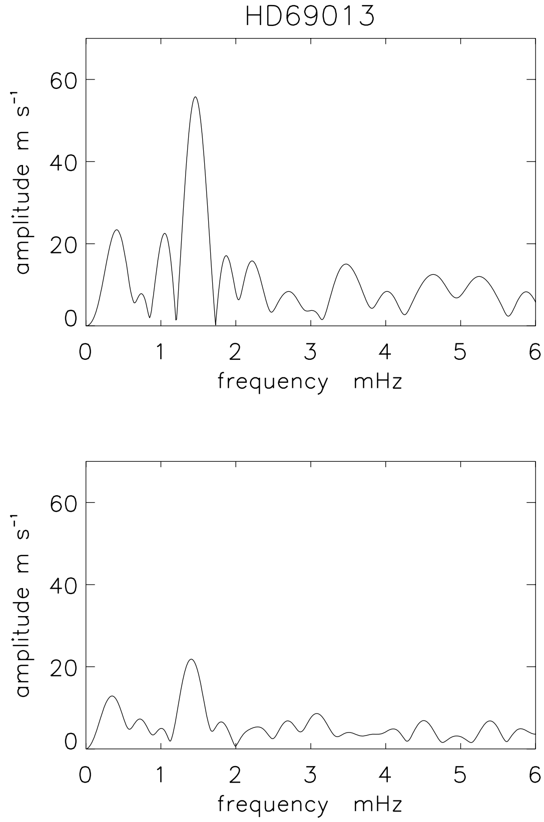

Figure 1. Top panel: the amplitude spectrum of HD 69013 obtained from cross-correlation over the spectral region 5000–5800 Å for the first observing run (see Table 1). An average spectrum was used as the template for the cross-correlation. The frequency peak is at $\nu = 1.46$ mHz. Bottom panel: the amplitude spectrum for the second spectroscopic run. The frequency peak is $\nu = 1.42$ mHz. The pulsation amplitude dropped significantly between the two runs, indicating rotational modulation or multiperiodicity.

3.1 HD 69013

Cross-correlation for the spectral band 5000–5800 Å with an average spectrum taken as a template shows obvious rapid oscillations for HD 69013, as can be seen in Fig. 1. For the two independent observing data sets that we obtained with the ESO VLT telescope we find in the amplitude spectra highest peaks at $\nu = 1.46$ and 1.42 mHz, correspondingly, with a full width at half-maximum uncertainty of 0.07 mHz. Hence these two independent peaks are at the same frequency within the frequency error.

The spectral lines of the rare earth elements also show pulsation with different amplitudes. The highest amplitude we detected was obtained for lines of Pr III, shown in Fig. 2, while lines of Nd III reveal a smaller amplitude as shown in Fig. 3. The other lines which belong to Eu II, Ce II, La II also show pulsations with significant peaks in the amplitude spectra.

The pulsation amplitude is smaller for the second observing run, which suggests either rotational modulation or multiperiodicity. While many Ap stars show rotational light variations caused by abundance spots usually associated with their magnetic poles, there is no such evidence yet found for HD 69013 (Freyhammer et al. 2008). This constraint is weak and does not rule out rotational

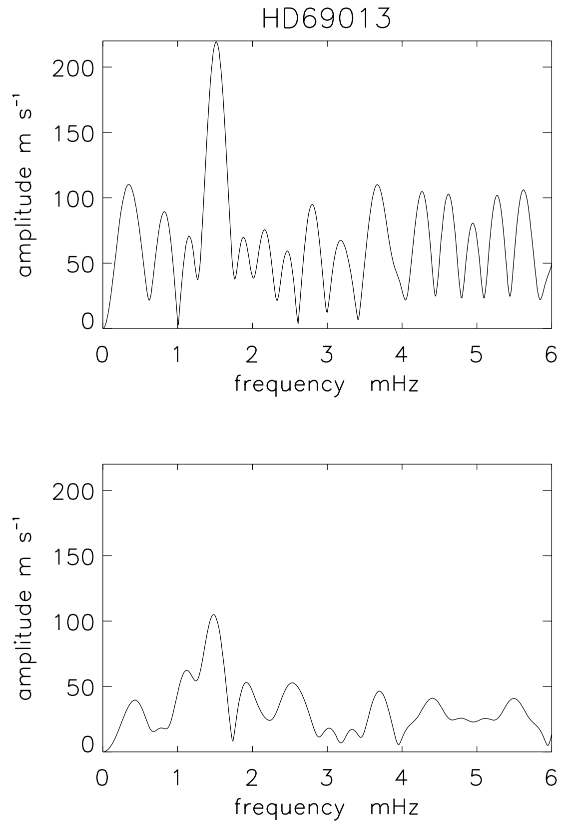

Figure 2. Top panel: the amplitude spectrum of HD 69013 obtained from the line of Pr III at λ5299.993 Å. The frequency peak is $\nu = 1.51$ mHz. Bottom panel: the amplitude spectrum for the second spectroscopic set of HD 69013 for the same line. The frequency peak is $\nu = 1.48$ mHz.

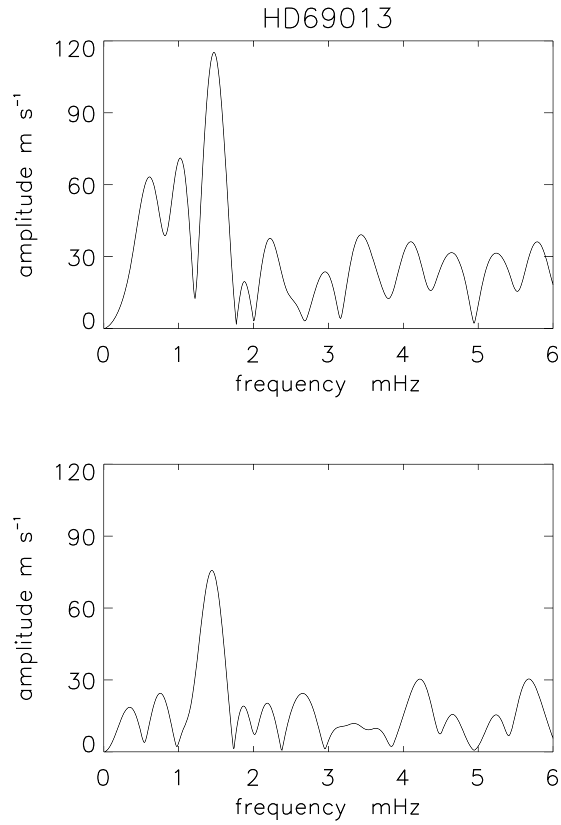

Figure 3. Top panel: the amplitude spectrum of HD 69013 obtained from three lines of Nd III (λλλ5050.695, 5102.427, 5294.113 Å) combined. The frequency peak is $\nu = 1.47$ mHz. Bottom panel: the amplitude spectrum for the second spectroscopic set of HD 69013 for the same three lines. The frequency peak is $\nu = 1.44$ mHz. Within the errors these two peaks are the same.

modulation of the pulsation amplitudes. Further observations are needed to study this question.

The photometric observations of this star obtained at SAAO also show rapid oscillations, as can be seen in Fig. 4. Previous photometric observations by Nelson & Kreidl (1993) and Martinez & Kurtz (1994) did not detect variations in this star. The amplitude spectra of our SAAO photometric observations are shown in Fig. 4. We obtained data on two nights. The first data set shows a signal at the same frequency as for the radial velocity data, but there is no significant peak in the second data set, as can be seen in Fig. 4.

3.2 HD 96237

The case for pulsation in HD 96237 is not as strong as for HD 69013, but all of the evidence together gives confidence that pulsation has been detected and this star is an roAp star. The five panels of Fig. 5 show amplitude spectra for spectroscopic analysis of HD 96237. Clear pulsation peaks were obtained from cross-correlation for the spectral region 5000–5600 Å using an average spectrum as a reference template, and for the core of the Hα line.

As mentioned above, the spectrum of HD 96237 is very rich in rare earth element lines. We tried to measure pulsations for individual spectral lines which were identified by comparison with synthetic spectra calculated with the SYNTH code of Piskunov (1992), but found that the pulsation amplitude is too low for clear detection in most individual lines, given the noise level in our spectra and relatively short observing run. In a few spectral lines of rare earth elements a peak corresponding the pulsation frequency detected by cross-correlation is visible in the amplitude spectrum, as can be seen in the third panel of Fig. 5 for a single Ce II line.

The combination of several good spectral lines reduces the noise level and produces a more reliable picture. The two lower panels in Fig. 5 show amplitude spectra for combinations of five rare earth element lines giving a clear peak. For twelve lines of Fe I and Fe II no pulsation is detectable, as is typical of the roAp stars.

As a further test, we examined a combination of several telluric lines and found that there is no signal above a noise level of 12 m s^{-1}. We conclude that the case that HD 96237 is an roAp star is good. Further studies – particularly at the rotation phase where the pulsation amplitude is highest – will give more confidence.

Photometric observations were obtained at SAAO for additional testing of pulsations in HD 96237. The frequency analysis of the photometric data listed in Table 1 is presented in Fig. 6. The upper panel of this figure supports the pulsation period found by spectroscopy, but other photometric observations shown in the bottom four panels and by Nelson & Kreidl (1993) do not detect pulsation in this star.

This can be understood in terms of rotational modulation in an oblique pulsator and/or beating of multiple frequencies. The pulsation amplitudes in many roAp stars are modulated with the rotation period of the star. Thus some of the photometric observations may not have been in best aspect. To judge this, the rotational period and ephemeris of HD 96237 needs to be determined. From the All Sky Automated Survey (ASAS) and *Hipparcos* photometry,

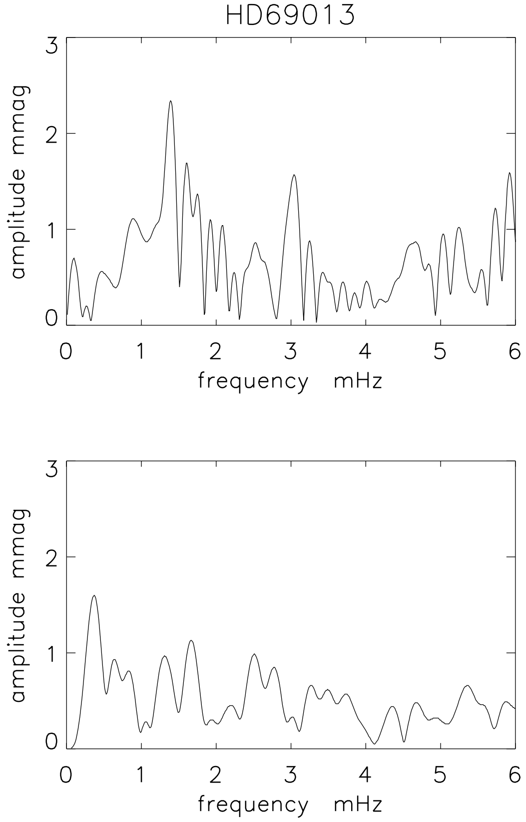

Figure 4. Top panel: the amplitude spectrum of HD 69013 obtained for the first run of SAAO photometry through a *B* filter. The highest peak has a frequency of 1.39 mHz. Bottom panel: the second photometric set for the star does not show any significant peak for frequencies close to that detected by spectroscopy.

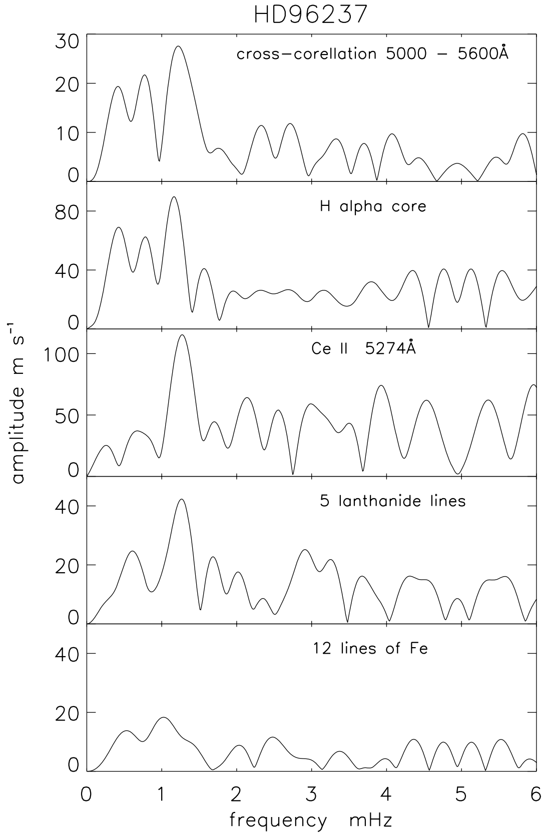

Figure 5. A cross-correlation and Fourier analysis for 34 spectra of HD 96237. From top to bottom: the first panel shows a highest peak with a frequency of 1.22 mHz; the second panel has a peak at 1.16 mHz which is consistent with the first panel within the errors. Both upper panels also show peaks with the frequency 0.78 mHz which is close to that detected in two photometric observations (see panels 3 and 4 of Fig. 6. The peaks in the third and fourth panels have highest peaks at a frequency of 1.27 mHz. The fourth panel shows an amplitude spectrum for a combination of lines – Nd III 5102.43 Å, 5294.11 Å, Pr III 5284.69 Å, 5299.99 Å, Nd II 5319.81 Å. No pulsation signal was detected for a combination of 12 lines of iron, as shown in the fifth panel.

Freyhammer et al. (2008) found photometric variations with a period of 20.91 d, which may be the rotational period. Using two seasons of data from the Wide Angle Search for Planets (WASP) project (Pollacco et al. 2006) covering the intervals 2007 January 4 to June 3 and 2008 January 5 to May 28, we obtained a similar period. Combining the WASP (passband from 400 to 700 nm) and ASAS (*V*-band) photometry we find the following rotational ephemeris for the photometric maximum:

$$\mathrm{HJD(phot.max.)} = 245\,4483.9285 + 20.91E. \quad (1)$$

The rotational phases calculated from this ephemeris are also shown in Fig. 6. The bottom panel is for data observed in the same rotation period as the upper panel, but does not display any pulsations. The spectral observations presented in Fig. 5 were also obtained at a similar rotation phase using the above ephemeris. Assuming our case for pulsation in this star to be good, we suggest two possible solutions: (1) the rotation period may not be 20.91 d, but double that. This ambiguity happens for some peculiar stars (see for example Wade et al. 1997). Longitudinal magnetic field measurements over the rotational period can resolve this, and (2) the star may be multiperiodic. There is some hint in Fig. 6 of a peak at 0.79 mHz. Additional observations are required to resolve these questions.

4 CONCLUDING REMARKS

The chemically peculiar magnetic star HD 96237 is an interesting object which has a very peculiar spectrum with significant spectral variability. The star demonstrates large overabundances of rare earth elements. A high-resolution spectrum obtained with the ESO 2.2-m telescope and FEROS spectrograph resembles the spectrum of another highly peculiar star, HD 101065. Abundances of Nd II and Nd III determined from this spectrum are even higher than in HD 101065. Other rare earth elements also show large overabundances similar to those found in HD 101065. Another spectrum of the star obtained with VLT UVES was significantly different from the FEROS spectrum with much less intense spectral lines of the rare earth elements (Freyhammer et al. 2008). The similarity of the spectra and chemical abundances of HD 96237 to those of HD 101065, which was the first detected roAp star, increases the interest of this star. It is not known what determines the pulsation amplitude of the roAp stars. While the principal periods of HD 96237 and HD 101065 are similar (13.6 and 12.1 min, respectively), their photometric and spectroscopic radial velocity amplitudes are very different.

Our results for HD 69013 demonstrate clearly that this is a new roAp star with a low pulsation amplitude. This star shows possible rotational modulation and may be a useful target to study pulsation behaviour over the rotation period.

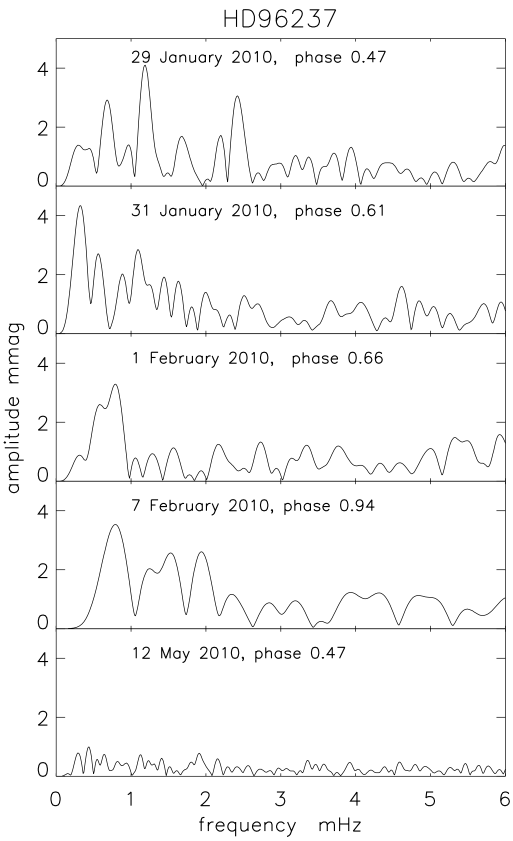

Figure 6. Amplitude spectra of the photometric observations for HD 96237. Extinction and sky transparency variations were removed using a second-degree polynomial. The data are ordered in time from top to bottom. The highest peak in the upper panel has amplitude near 4 mmag and frequency of 1.19ṁHz, which is at the error limit of the frequency found for the spectroscopic data. The star may also show a harmonic with a frequency of 2.42 mHz. The third and fourth panels show peaks with the same frequency of 0.79 mHz. A similar frequency peak was detected in spectroscopic observations (see Fig. 5). It is not clear whether this peak is real; only one other roAp star, HD 116114, with a similar low frequency has previously been found (Elkin et al. 2005).

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